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AN EXAMPLE OF PREDICTIVE RATHER THAN RESPONSIVE SAFETY RESEARCH FOR FUSION ENERGY SYSTEMS

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Summary

We believe that a research protocol must be established where safety technology is developed at a parallel rate to engineering and scientific advances of emerging energy systems. Safety sciences are traditionally given low priority during the developing stages of new technologies. Indeed, safety efforts are often considered counter productive, and funding for safety equipment and programs are not proportional to overall project budgets; i.e., minimum safety requirements are generally specified by local and/or federal codes. All project funding is allocated such that safety programs always meet the minimum standards. Seldom is a safety posture in excess of minimum standards considered.

The Department of Energy (DOE) attempted to initiate a positive energy safety program in 1975, when the Fusion-Laser, Safety Coordinating Committee (FL/SCC) was inaugurated. The purpose of the FL/SCC was to identify hazards unique to fusion energy experiments and future fusion power reactors, and to recommend research programs to develop countermeasures for the hazards. However, the FL/SCC died in approximately two years because of lack of interest.

Concurrent to and persisting after the efforts of the FL/SCC, the Operational and Environmental Safety (OES) Divison of DOE supported a modest effort at the Lawrence Livermore Laboratory (LLL) to study the fire risk of generic fusion energy experiments. The goals of this program parallel those of the FL/SCC only in the specific areas of fire risk, and developing fire countermeasures.

We used a fault tree analysis (FTA) to study the fire-management systems of two LLL fusion experiments (2XIIB and SHIVA). This technique identified failure modes of existing system components and indicated what the effects of component failure might be in the event of fire in the protected spaces. This paper describes the results of the initial analytical phase of the project and indicates critical unknown parameters required for further analysis. Moreover, the analytical procedures we have developed are applicable to most, if not all, safety disciplines and could serve as a basis for the logical reestablishment of the FL/SCC by DOE.

Introduction

An electrical failure occurred in the polystyrene insulation between a high voltage capacitor connector and the capacitor supporting rack in a capacitor bank test facility. A high-voltage arc developed, igniting the polystyrene. The energy and duration of the subsequent fire was sufficient to fuse a fire sprinkler, which extinguished the fire. The actual sequence of events leading to the fire has not been defined but it was determined that:

- It was the result of an unknown electrical fault.
- The fire growth rate was slow so that smoke production was large.
- The fire was first indicated by an electrical interlock failure.
- Costs ($23,000) were confined to repair of: structural supports, minor electrical components, soot and water damage, and fire department venting procedures.

Fortunately, the fire site was isolated so that the smoke was confined to the capacitor enclosure, thus there was no communication of smoke or heat to laser components. The facility was sprinklered and of relatively low volume. Physical damage was slight but programmatic delay was substantial. Smoke detectors have now been installed so that operators will have a much earlier indication of electrical faults with the potential for initiating destructive fires.

The above event is typical of the fire experience record for DOE-funded energy technology experiments. (Indeed, the fire record for all DOE facilities is much better than the general U.S. industrial experience, and they average far less than the $23,000 incurred above.)[1] However, in this case we failed to recognize the substantial loss that can accrue from a rather benign fire; after we experienced the event, we recognized and funded effective countermeasures. Therefore, we are guilty of practicing responsive rather than predictive fire-safety procedures. Clearly, the reverse ought to be the rule.

The current status of contemporary fire-management strategies is based on data from residential and industrial fire experience. Many fire-management components have been pragmatically developed and consist mostly of active measures to detect and/or extinguish fires. Figure 1[2] illustrates the range of management components available. Which system best fits the variety of situations faced by fire-protection planners is, at best, a matter of experience, and in general, guesswork.

In large, government funded energy technology experiments, fire-management systems are defined by

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recommended practice and standard documents generated by DOE. This guidance is constrained by lack of direct fire experience. Moreover, the types and sizes of fires expected in these systems are unknown. For these reasons DOE is supporting a study by the Fire Science Group (Hazards Control Department) of LLL to determine the fire hazards of current and future energy technology experiments, and the ability of accepted fire-management strategies to meet and negate the hazard.

Approach and Analysis of the LLL System

The knowledge required to adequately rate fire-management systems includes a sufficient understanding of:

- The fire-risk variables.
- The reliability of the fire-management system and system components.
- The effectiveness of the countermeasures on demand.

We approached this task assuming that some of these parameters would be understood; however, this was not the case. Moreover, even if they were defined, we would have to provide for intangible modifiers such as:

- Common mode failures (natural disasters, rodent attack, etc.).
- Human error.
- Impediments due to the potential for toxic exposure and/or release.

We essentially ignored these intangible factors and proceeded to seek a consensus of current fire-risk concerns from operators of fusion experiments. Table 1[3] lists the accumulation of fire-risk parameters as determined from our brief survey. The table is divided into categories that include near- and far-term fire risks for general energy technology experiments, and categories specific to inertial- and magnetic-confinement experiments. Abundant in this list are questions about the growth- and smoke-release rate of fires on materials common to fusion experiments. In a subsequent survey of fire growth models for residental fire-hazards analysis, hard data on fire growth rates were found to be crucial. For the major flammable materials resident in fusion experiments (electrical and thermal insulations), no flame spread data exists.

Figure 2[4] gives a frame work for fire growth analysis that indicates the type of data needed for developing hypothetical fire scenarios. All of these factors are interactive, thus, with the data currently available, we can only predict the order of magnitude characteristics of fire growth. The growth parameters follow exponentially increasing functions and are roughly corroborated by industrial and military experimental fire experience. An important dependent fire growth parameter is instantaneous heat release, and given the rate of heat release we can calculate approximate temperature rise and temperature gradient in the plume gases and heat transfer to the ceiling of the structure. Radiant ignition of adjacent items and copious smoke production are likely, but we have yet no way of quantifying these factors without even very rough models.

We thought that there would be abundant data available for assessing the reliability of existing and installed fire protection systems; however, we were again wrong. There was historical data available from insurance companies and trade associations that indicated sprinkler system reliability over a wide range of applications, but these data do not define critical components nor the consequence of failure of subcomponents to the overall system. (Note, when we refer to system reliability, we simply mean that the system operated at the proper time. Its effectiveness was not indicated in the data we obtained.)

To assess the reliability of fire-management systems we applied the FTA to installed fire protection systems for fusion experiments at LLL. This analysis was applied to both wet- and dry-pipe sprinkler systems. In dry-pipe systems, water is not allowed above a special inlet valve to the system until a sprinkler head is fused (thermally opened). When this happens, the air pressure in the water conduit is released allowing water to enter the system via the inlet valve. A schematic of an LLL dry-pipe system is shown in Figure 3. A wet-pipe system contains water throughout the system at local water pressure. When the sprinkler head is fused water is released directly to the fire site. Dry-pipe systems are used in cold climates where freezing temperatures are possible; modified dry-pipe systems (like the one shown in Figure 3) have been designed to reduce the probability of inadvertent release of water to high-tension electrical components. To get water flow through the system, both a signal from the resident smoke detector and air-pressure release by fusing the sprinkler head must occur. Either event will cause a signal to be transmitted to the central emergency control panel, mobilizing the LLL Fire Department. This is, in fact, the desirable response, because we anticipate that the smoke detectors are most likely to sense the combustion products of incipient fires before accelerated growth to high heat release occurs.

Qualitative and quantitative FTA's of this fire-protection arrangement reveal that the electronic circuits of the zone- and fire-indicating units are critical couplers to the electrical/mechanical components of the system. At least 713 system failure modes were identified for a unit model of the entire fire-management scheme. Forty-two of the failure modes were single-point failures (i.e., a single component failure can result in the failure of the entire system). Almost half of these single point failures were in the electrical components of the zone- and fire-indicating units. Quantitative analysis of the system unavailability upon demand and the importance ranking of basic events and fault modes leading to system failure were calculated using available reliability data from:

- The National Fire Protection Association
- IEEE Standard 500
- UKAEA Standards (United Kingdom)
- Factory Mutual Insurance Corporation
- Wash 1400
- Facililty P&IE specification
- Direct conversation with the maintenance crew and LLL Fire Department

Using codes specific to quantitative FTA[5,6] we calculated that the probability of this system failing on demand (i.e., in the event of a fire) is 0.18 and that nine basic events contributed to system failure.

A similar analysis was made of a laboratory wet-pipe system. Because of reduction in complexity of the response requirements, the reliability of this system is substantially higher, and the probability of system failure is only 0.02 based on the same component-reliabilty data. The calculated probability of an accidental release of water was of the order of 10^{-5} per year for both systems.

We compared our calculations with the available historical data. Our results were embarrassingly close to these published values (i.e., for wet-pipes we calculate a reliability of 98% and the average of historical data are 96%; similarly for dry-pipe systems our calculations indicate a reliability of 82% while historical data averages 86%. We were unable to find any solid data for the probability of accidental release, however, inquiries of sprinkler manufacturers confirm that our calculated probabilities are of the right order.

Based on the findings of this analysis for the modified dry-pipe system, LLL magnetic fusion administrators have authorized its replacement by a more effective and economical wet-pipe system.

Relating the fire growth analysis to the response parameters of the fire management system shows a wide variation in the range of sprinkler response times. Because of the uncertainty in the model, the time range for initiation of water application varies from 8 to 30 minutes. As indicated before, we expect that the smoke detectors would have already signaled the Fire Department, and their actions would negate the need for sprinkler activation.

A quantitative measure of the effectiveness of applying extinguishing techniques, by either the designed sprinkler system or the Fire Department is impossible because of potentially varying modifying factors. Experience and common sense tell us that the earlier the fire suppression agent is applied to the fire, the quicker it is controlled. These observations should have been sufficiently compelling to have motivated experimental operators and administrators to plan and install optimum fire protection for their systems. But in this paper, we have illustrated two cases where extensive parametric analysis, or experience with an accidental fire were required to supply the necessary leverage to upgrade the modifications of the fire-protection components to a more effective level.

Applications and Conclusions

One of the goals of this analysis is to develop a means of comparing the match between fire risk and the potential effectiveness of a fire-managment system. In generic fusion experiments, our approach is to construct a fault-tree model that reflects the reliability of components in a total fire-protection system. We then attempt to conceptually overlay a specific fault tree constructed for the facility we are analyzing. Where our systems coincide, we can transpose our reliability factors and fire risk approximations directly. Where the subject system is completely unrelated, we take particular note and attempt to define and assess the effects of the unrelated factors. The following outline sketches our first cut analysis of the fire-protection stratagies of several contemporary fusion experiments.

(A) Sandia EBFF
Fire Hazard: Marx generators, capacitors, large quantities of cable insulation and dielectric fluid in open reservoir, frequent fluid transfer, boiler room close to dielectric reservoir and fire main. Ventilation: HVAC. Detection/Suppression: Smoke detectors in screen room, central water-flow alarm, wet-pipe with AFFF*, 5-min Fire Department response, standpipe, water reservoir. Reliability: Simple wet-pipe system for large fires $\approx$95%/demand, high bay 40 ft ceiling, small fire could cause damage before sprinkler alarm is activated. Effectiveness: Aerosol explosion could remove wet-pipe system, unknown potential of low-intensity fire. Modifiers: AFFF corrosion potential, maintenance errors (Marx generator service), weather could slow Fire Department response.

(B) Princeton TFTR
Fire Hazard: High energies, thermal and cable insulation, local ^{3}H concentration, electric arcs. Ventilation: HVAC. Detection/Suppression: Local and central alarm, preaction dry-pipe sprinklers, smoke detectors, freon type extinguishers in specific and sensitive areas, 10 min Fire Department response. Reliability: Preaction sprinklers $\approx$85%/demand. Effectiveness: Poor location of detectors and sprinkler heads could lead to large loss. Fire Department several miles away. Modifiers: Weather/traffic could slow Fire Department.

(C) Lawrence Livermore 2XIIB:
Fire Hazards: Many wood structures, cable insulation, plastic sheets and cable trays, (local) high-power densities. Ventilation: HVAC. Detection/Suppression: Local and central alarm, modified preaction sprinkler system, smoke detectors throughout. Reliability: Modified dry-pipe preaction system $\approx$82%/demand (soon to be changed to total wet-pipe system). Effectiveness: Forty foot ceiling height could allow small fire to cause damage. Modifiers: Minimal due to dedicated systems.

(D) Max Plank IPP: Tokamak and Stellerators, Iodine lasers. Fire Hazards: Cable and thermal insulations. Ventilation: HVAC. Detection/Suppression: Local alarm, few hose hookups, 10-15 min Garshing Fire Department response. Modifiers: Late detection, traffic, weather.

(E) CEN-G Tokamak: Plasma studies. Fire Hazards: Cable and thermal insulation. Ventilation: Windows. Detection/Suppression: Thermal detectors, dry chemicals on carts, five men on site. Modifiers: Weather, multiple fires, late detection and inadequate suppression.

(F) Culham MFE:
Fire Hazards: Cable and thermal insulation and many experiments. Ventilation: Melt-out windows. Detection/Suppression: Eight-man patrol, minimal automatic detection, local alarm, manual standpipes. Modifiers: Fire Department remote from site. Obscuration of fire site in large fusion experimental area.

This tabulation indicates that:

- The combustible material load, and consequently the fire risk parameters, at early times are quite similar for all systems (E-beam open oil reservoirs excepted).
- European fire protection systems rely primarily on early warning from fire detectors rather than automatic extinquishing systems.
- Areas without dedicated fire-fighting personnel and equipment could suffer extensive property loss should the resident automatic extinquishing system fail.

- The effect of unique features of experiments and experimental enclosures can be identified but not quantified at this stage of the analysis.
- No human error modifiers are listed because of our inability to locally place such factors in our analysis.

We are currently engaged in research of the physical characteristics of: fire growth and smoke production by electrical insulations; fire dynamic interaction with enclosures modified by various imposed ventilation changes; corrosion potential of smoke from various insulation polymers; and the minimum ignition criteria of electrial insulation. With these data applied to our fire growth models, we should be better able to predict fire risk in fusion experiment enclosures, and as a result, have the key to assess the relative effectiveness of the total fire-management systems.

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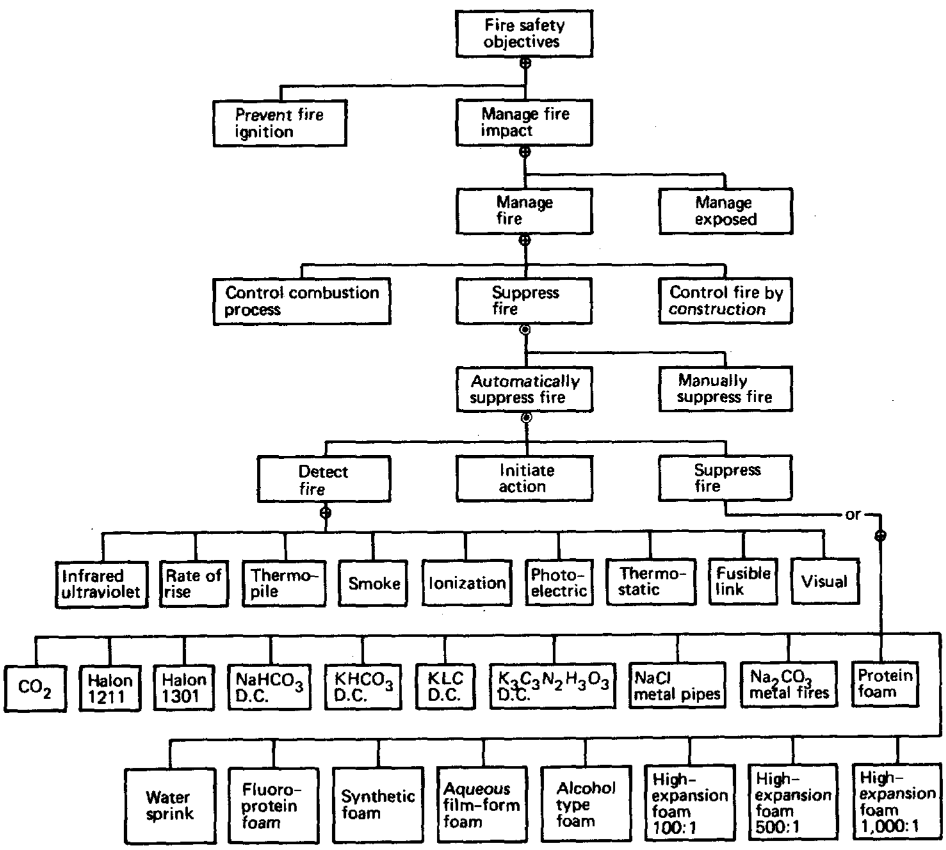

Figure 1 Decision Tree of Fire Management System

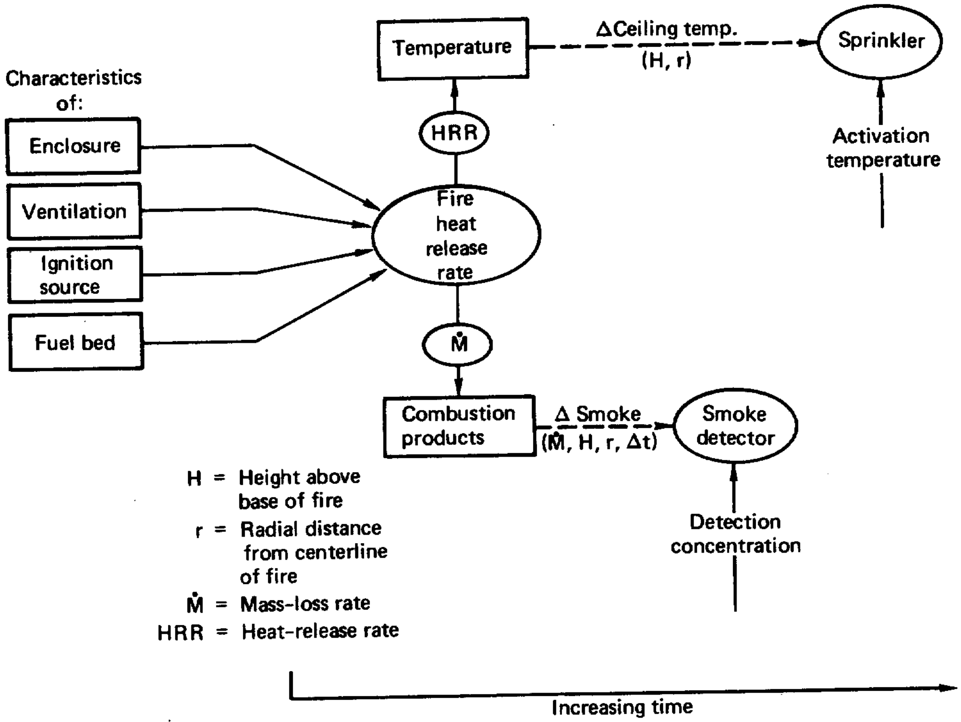

Figure 2 Framework for Fire Growth Analysis

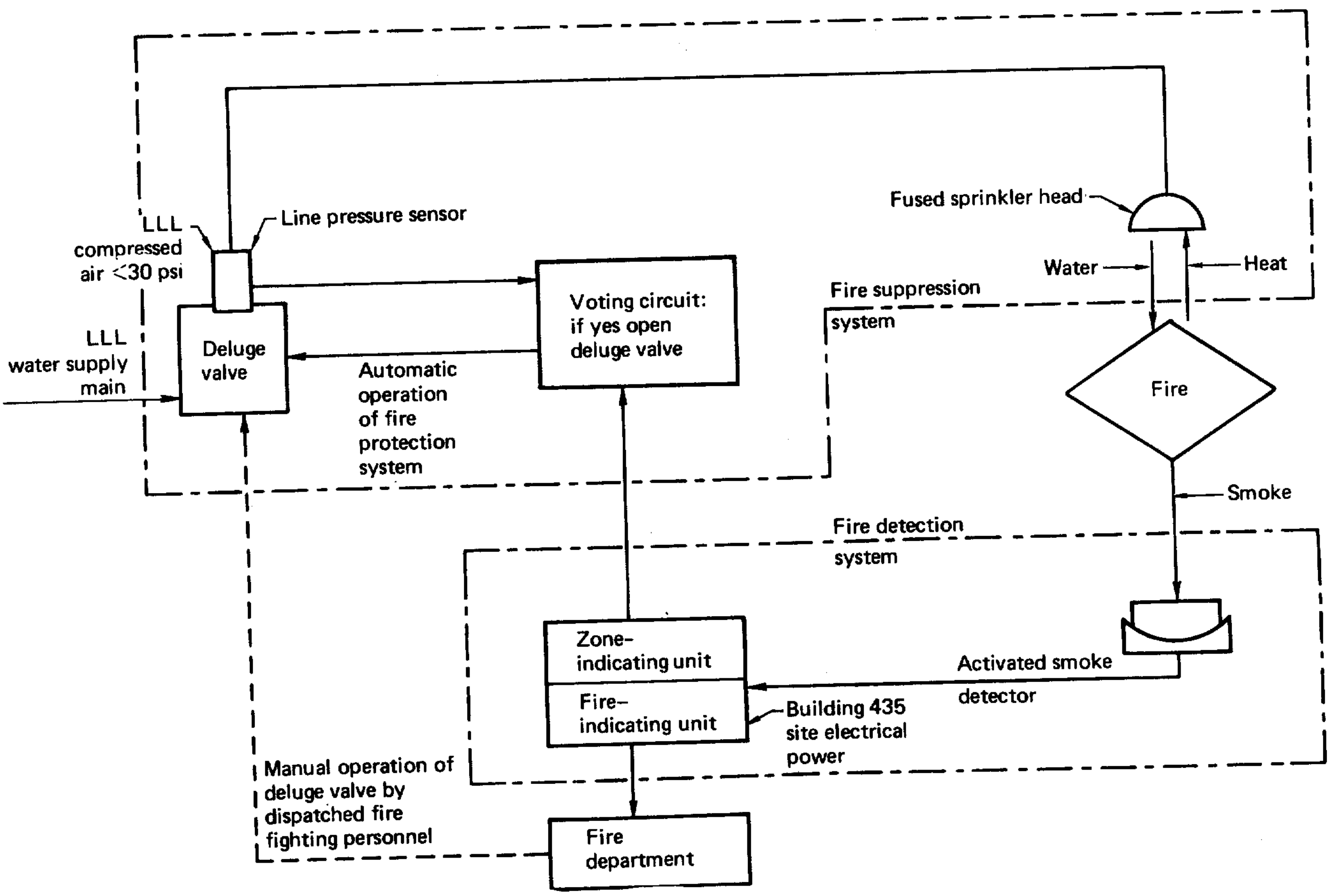

Figure 3 Schematic of 2XIIB Fire Protection System

TABLE 1

POTENTIAL FIRE HAZARD IN FEE AND FUSION POWER REACTORS (FPR)

	NEAR-TERM	FAR-TERM
General		
	Lack of adequate fire protection measures during construction of FEE buildings.	Potential for transient signal generation from burning cables to FEE and FPR.
	Unknown flammability characteristics of electrical and thermal insulations. Of specific concern: (1) Rates of; flame spread, heat release, smoke evaluation, in the configuration of their common use. (2) Toxic and Corrosive potential of the variety of smokes. (3) Shorting potential of pyrolized electrical insulation.	Combustion and extinguishing characteristics of liquid metals in condensed and vapor phase. Problems associated with impurity extraction from liquid metal breeding and/or heat transfer media.
	Electrical conductivity of extinguishants applied to apparatus holding high electrical charge.	Development of fire-management systems that can discriminate between different types of fires.
	Early warning fire detectors that operate in ionizing radiation fields.	Fire hazards of FEE and FPR support facilities (i.e., cryogenic storage, extraction plants, pellet fabrication facilities).
	Detonation and deflagration characteristics of dispersed aerosols of capacitor, transformer and vacuum oils.	New electrical component interaction in complex control systems
Magnetic Confinement		
	Mobile fire management for quick change capabilities due to experimental changes.	Corrosive potential of smokes from pyrolyzing insulations on sensitive electrical components.
	Inert containment strategies for dielectric oil reservoir applications.	Retractable partitions to devide high bay areas into manageable zones in the event of fire alarms.
		Fire hazards in liquid metal heat transfer loops.
		Detection and extinguishment of fires due to ^3H release.
Inertial		
	Corrosive potential of smokes on laser components.	Zonal fire-management systems specific optical to laser systems.
	Corrosive potential of extinguishants on laser optical components.	